ExoPlanet Exploration Program

# AFTA Coronagraph Preliminary Design
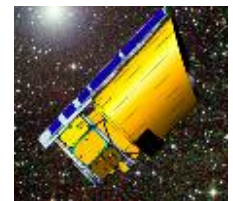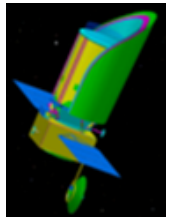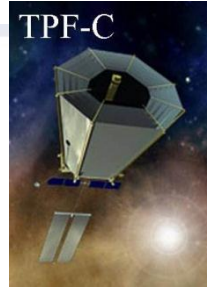
## WFIRST SDT Meeting #1

November 20, 2012

Marie Levine

Stuart Shaklan

National Aeronautics and Space Administration
**Jet Propulsion Laboratory**
**California Institute of Technology**

**ExoPlanet Exploration Program**

- 2004-07: Terrestrial Planet Finder Coronagraph (TPF-C) SDT
  - Flagship: 8x3.5m off-axis
  - Primary Goal: Earth detection and characterization
  - Coronagraph: Lyot mask at 4 $\lambda$/D and $10^{-10}$ Contrast
  - Requirements and performance well understood.
  - Modeling capabilities for error budgets & performance

- 2008-09: Astrophysics Strategic Mission Concept Studies (ASMCS)
  - Several probe-scale coronagraph studies (<$800M – $1B)
  - ACCESS (Lyot), PECO (PIAA), EPIC (Visible Nuller)
  - Approach: ~ 1.5m Telescopes, < 3 $\lambda$/D and $10^{-9}$ Contrast
  - Science Goals: Jupiters & some Super-Earths detection & characterization, Exo-Zodi, Planetary Systems

- 2011- on-going: Exoplanet SDT
  - Flagship Mission Requirements (2012, Greene & Noecker)
  - Probe Mission Requirements (2013-14)


TPF-C


**ATLAST**


**EPIC**


**PECO**

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**ExoPlanet Exploration Program**

- Main objective: EXISTENCE PROOF

  – Demonstrate feasibility, science, performance and cost of <u>a</u> coronagraph instrument on WFIRST-AFTA

- Time & funding will permit only 1 design cycle

  – Future studies will consider more aggressive & riskier coronagraphs which optimize science & performance

- FOR NOW Use Lyot coronagraph layout: best understood, models validated and applicable to several coronagraph types:

  – Lyots, Shaped Pupil and Vector Vortex share same configuration
  – PIAA and Visible Nullers require unique optical configurations

- Coronagraph Instrument consists of 3 components:

  – Coronagraph for broadband starlight suppression
  – Low Order Wave Front Sensor (LOWFS) for tip/tilt pointing and later possibly low order aberration control
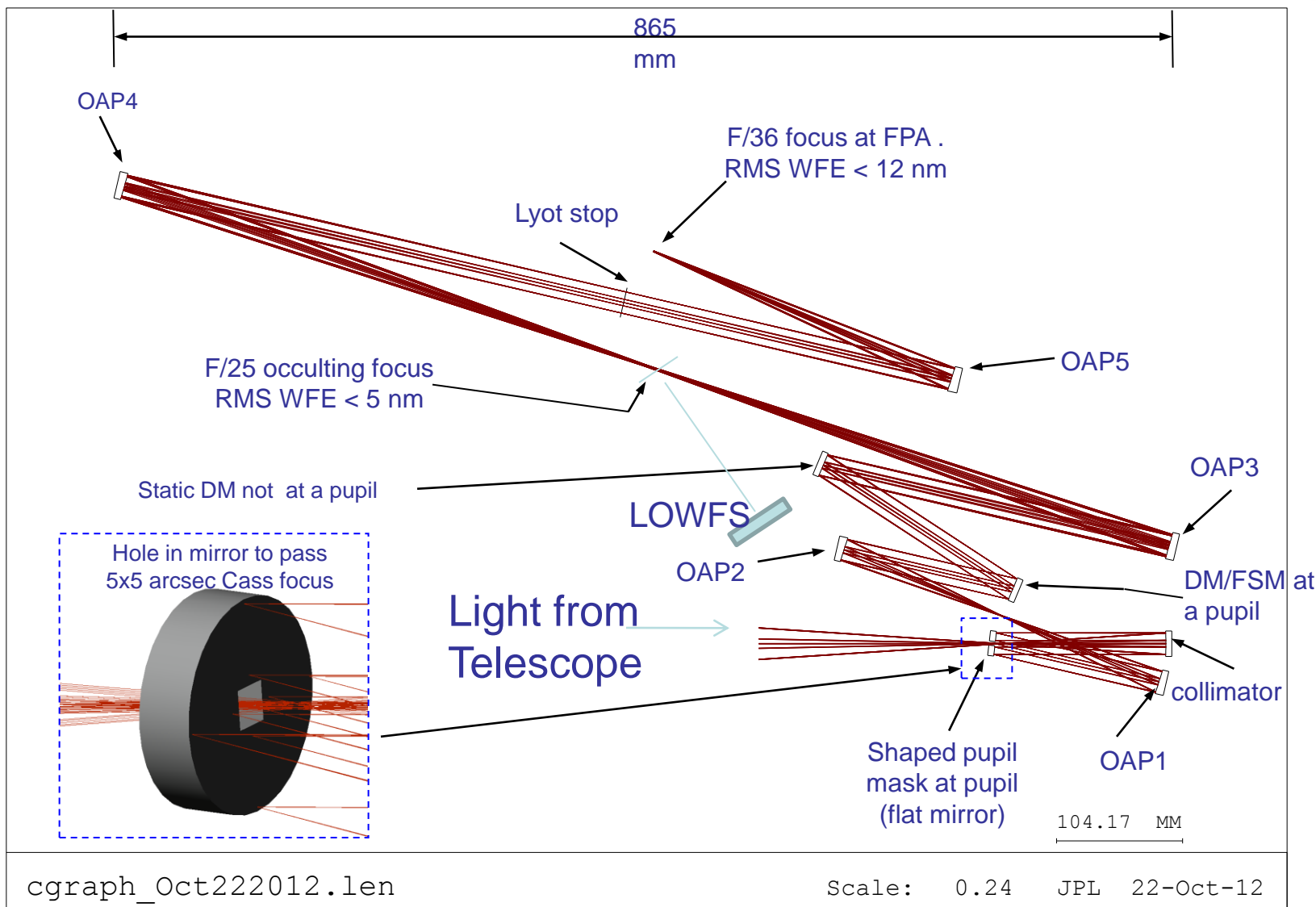  – Integral Field Spectrometer for characterization

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| Bandpass | 400-1000 nm | Will likely require sequential measurement in 20% wide bands |
|---|---|---|
| Inner Working Angle | 100 mas | at 400 nm, 3 $\lambda$/D driven by challenging pupil |
| | 250 mas | at 1 um |
| Outer Working Angle | 1 arcsec | at 400 nm, limited by 64x64 DM |
| | 2.5 arcsec | at 1 um |
| Contrast | 1.E-09 | Cold Jupiters, not exo-earths. Deeper contrast looks unlikely due ot pupil shape and extrememe stability requirements. |
| Spectral Resolution | 70 | at 700 nm.  Linearity TBD. |
| IFS Spatial Sampling | 17 mas | This is Nyquist for $\lambda$ 400 nm. |

Levine/Shaklan

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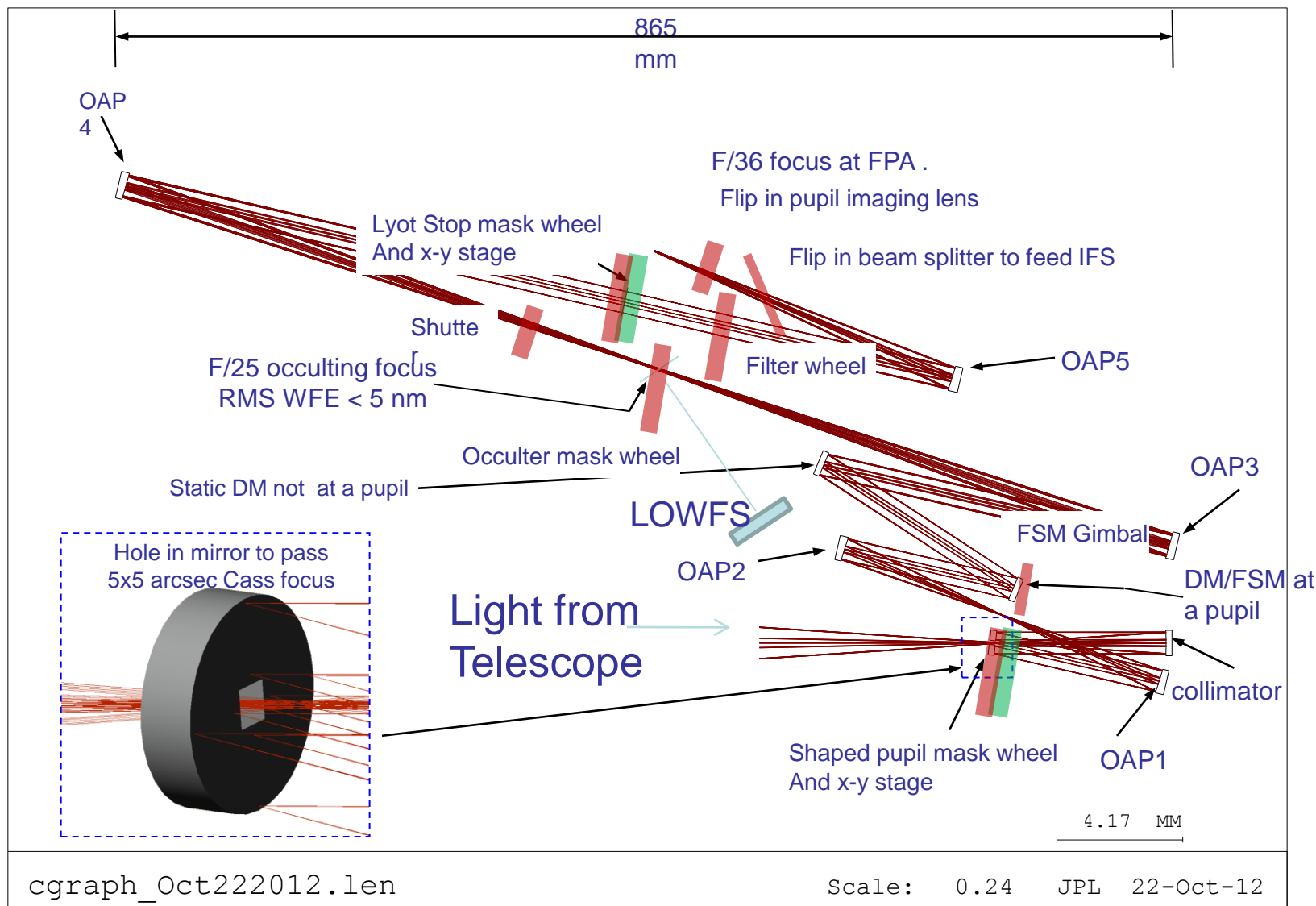
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| | |
|---|---|
| Coronagraph Type | Designed to support Lyot and shaped pupil coronagraphs. Lyot has best performcne to date. Shaped pupil may be superior for the complex obcurations of this telescope. |
| Operating Temperature | Room Temperature, due to DM wavefront specifications. |
| Deformable Mirrors | Two 64x64 devices, sequentially placed for broadband dark hole control. Current design is for MEMS DM with 300 um pitch. Design is larger for 1 mm pitch Piezo DM. |
| Detectors | Direct Imaging: 1K x 1K visible detector, 12 um (TBR) pixels<br>Low Order Wavefront Sensor:  E2V 39, 24 um pixels<br>IFS: 2K x 2K detector, ultra-low noise |
| Mechanisms | Shaped Pupil Filter Wheel: 4 position (TBR)<br>Lyot Stop Filter Wheel: 3 position (TBR)<br>Bandpass Filter Wheel: 10 position (TBR)<br>Tip-tilt gimbal: +/- 6 arcsec (TBR), allows for 0.1 arcsec telescope rigid body pointing error). 40 mas resolution.<br>IFS beam splitter mechanism: 2 position<br>Pupil imaging lens wheel: 3 position (TBR)<br>Shaped Pupil x-y stage, 10 um resolution<br>Lyot Stop x-y stage, 10 um resolution<br>Lyot image plane mask wheel, 3 position (TBR)<br>Shutter for FPA |

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865 mm

OAP4

F/36 focus at FPA .
RMS WFE < 12 nm

Lyot stop

F/25 occulting focus
RMS WFE < 5 nm

OAP5

Static DM not at a pupil

OAP3

LOWFS

OAP2

DM/FSM at a pupil

Hole in mirror to pass
5x5 arcsec Cass focus

**Light from Telescope**

Shaped pupil
mask at pupil
(flat mirror)

collimator

OAP1

104.17 MM

cgraph_Oct222012.len

Scale: 0.24    JPL    22-Oct-12

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865 mm

OAP 4

F/36 focus at FPA .

Flip in pupil imaging lens

Lyot Stop mask wheel
And x-y stage

Flip in beam splitter to feed IFS

Shutte

Filter wheel

OAP5

F/25 occulting focus
RMS WFE < 5 nm

Occulter mask wheel

OAP3

Static DM not at a pupil

LOWFS

FSM Gimbal

Hole in mirror to pass
5x5 arcsec Cass focus

OAP2

DM/FSM at
a pupil

Light from
Telescope

collimator

Shaped pupil mask wheel
And x-y stage

OAP1

4.17 MM

cgraph_Oct222012.len

Scale:  0.24   JPL  22-Oct-12

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## Xinetics, 64x64 DM

In hand:  several 32x32, one 48x48,
One 64x64 currently in use in HCIT
     pixel pitch:  1000 um
     stroke: ~1.5 um
     Mirror segment: glass on PMN
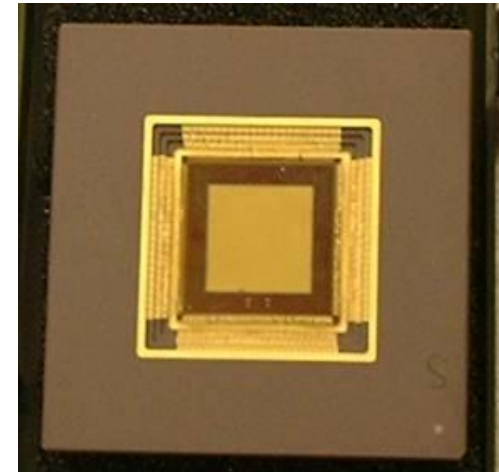


## Boston Micromachine 32 x32 MEMS

Phase II SBIR has begun. Delivery of 3000
element continuous facesheet MEMS DM in 2014.
          pixel pitch: 300 um
          stroke :        1.5 um
          Mirror segment  material: silicon
Many 32x32 devices in use: Princeton, LLNL, UA,
UH, ARC

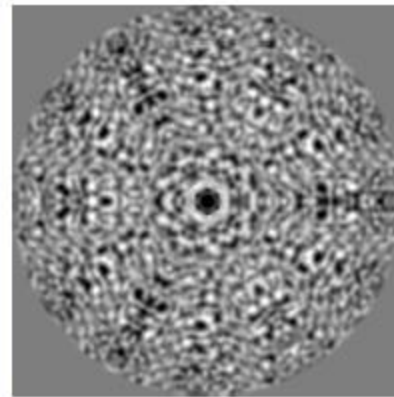# Coronagraph Masks Design

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**Lyot Coronagraph**: complex mask (amplitude and phase) to address obscured aperture. A monochromatic solution has been found and is shown here.  Broad band solution is being addressed.  *Courtesy of J. Trauger and D. Moody, JPL.*
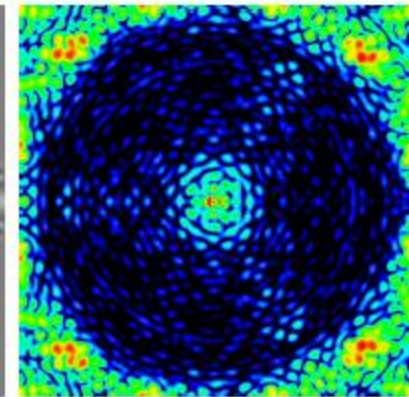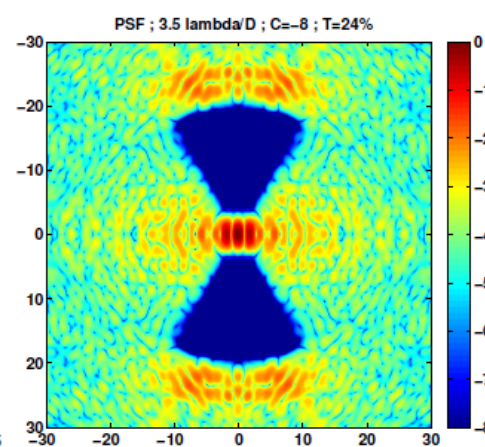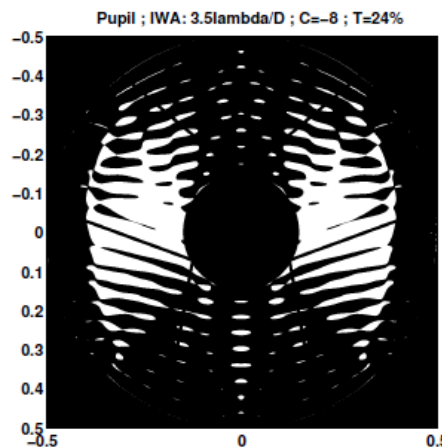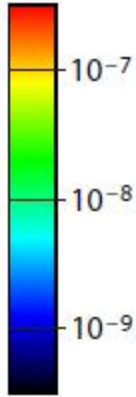


TELESCOPE APERTURE & LYOT MASK
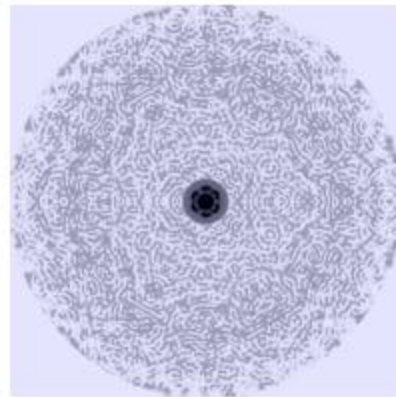
LYOT FOCAL PLANE MASK (TRANSMITTANCE)

LYOT FOCAL PLANE MASK (PHASE SHIFT)

HIGH CONTRAST DARK FIELD



Pupil ; IWA: 3.5lambda/D ; C=-8 ; T=24%

PSF ; 3.5 lambda/D ; C=-8 ; T=24%

**Shaped Pupil Masks**:  A binary apodization in the pupil plane is optimized to provide high-contrast attenuation over a prescribed region of the image plane. Naturally broad band, trades IWA, throughput, contrast, and discovery area. *Courtesy J. Kasdin and A. Carlotti, Princeton.*

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- Follows design principles of ground-based IFS instruments, e.g. CHARIS (Princeton), GPI, SPHERE. OSIRIS

- 140 x 140 lenslet array. Designed to disperse 20% band over 24 detector pixels (SR ~70).
  - Accommodates 0.4 – 1 um range using 4 bandpass filters (one at a time)
  - 17 mas 'spaxel' pitch.

Meadows, 2006
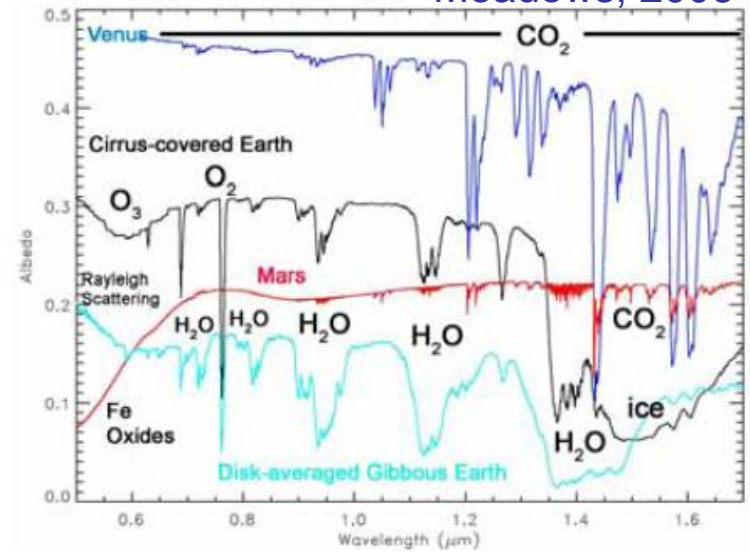


| Wavelength | Spect. Resol | Species | line depth | At this abundance level |
|---|---|---|---|---|
| 0.58 | 5 | O3 | 0.112 | 3 ppm |
| 0.69 | 54 | O2 | 0.088 | 10% |
| 0.72 | 37 | H20 | 0.13 | 1000 ppm |
| 0.73 | 57 | CH4 | 0.07 | 1000 ppm |
| 0.76 | 69 | O2 | 0.388 | 10% |
| 0.79 | 29 | CH4 | 0.032 | 1000 ppm |
| 0.82 | 35 | H20 | 0.118 | 1000 ppm |
| 0.89 | 32 | CH4 | 0.417 | 1000 ppm |
| 0.94 | 17 | H20 | 0.401 | 1000 ppm |
| 1.05 | 40 | C02 | 0.001 | 1000 ppm |

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| Property | IR |
|---|---|
| Wavelength coverage (μm) | 0.4-1.70 |
| Field of view | 3.0" × 3.0" |
| Spatial resolution element (arc sec) | 0.15 |
| Spectral resolution, $\lambda/\delta\lambda$ | 100 |
| Cumulative optical throughput | 55% |

Table 1: Spectrograph main specifications.

- Longer bandpass, 1.7 vs. 1.0 um

- Coarser pixels, 0.15 vs. 0.017 arcsec

- Higher Spectral resolution, 100 vs. 70

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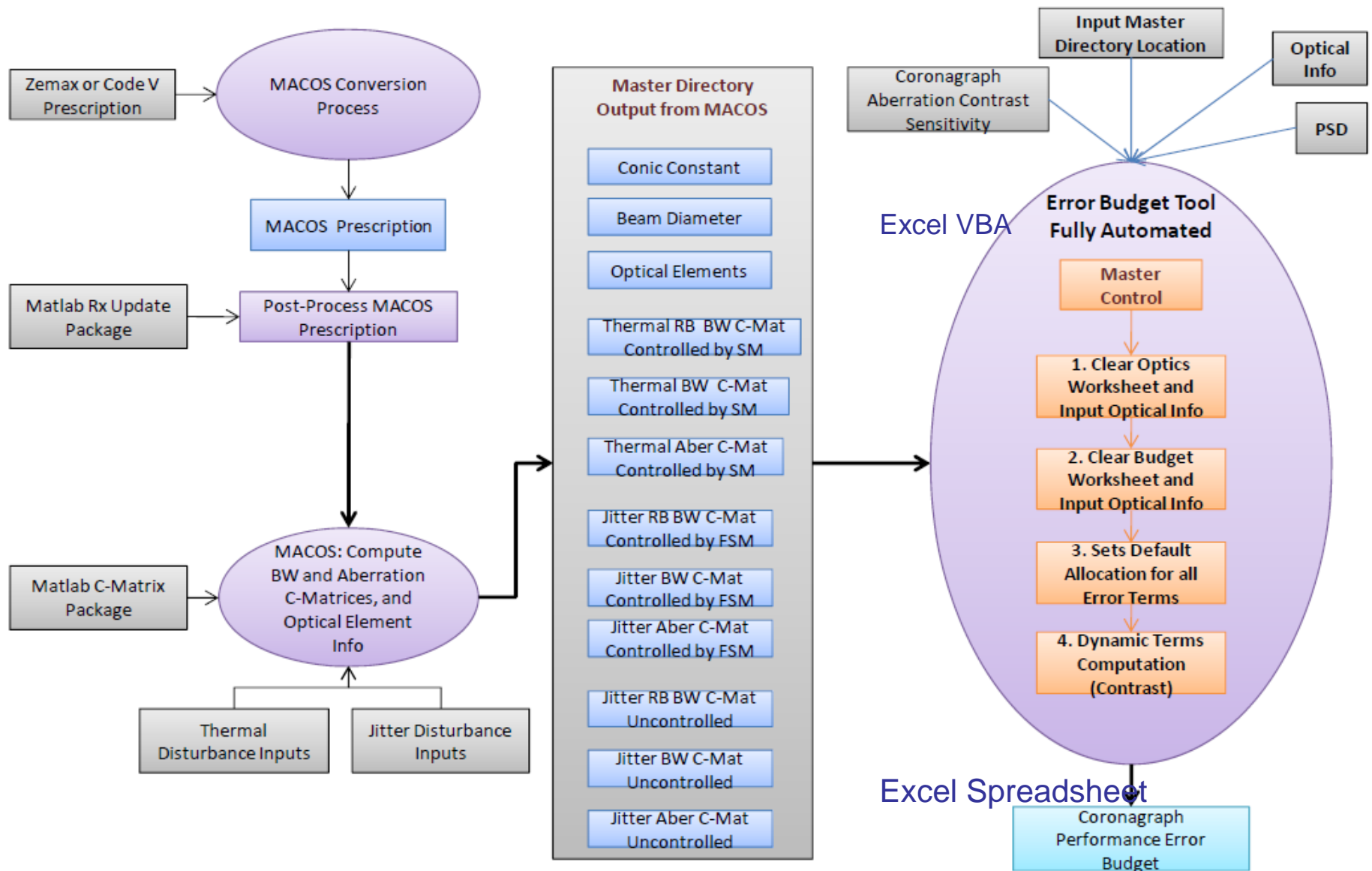
- Allocation for observing a 1e-9 contrast planet with systematic-floor limited SNR = 5, at 3 $\lambda$/D
  - Assumes we can start the observation with mean contrast level of 2e-10 and std. dev. of 1e-10.

  - We determine changes in the state of the system that raise the std. dev to 2e-10. *This is the final systematic floor.*

- Assumes ideal radial band-limited Lyot coronagraph for unobscured aperture.
  - A Lyot coronagraph accounting for real pupil will make things worse.

  - A shaped pupil could potentially make things better but it remains to be seen if one can be designed to achieve better than 1e-9 residual. Perhaps the DM can 'dig' a dark hole in the diffraction pattern.

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## Top contributors to image plane scatter non-uniformity
## Requirement: speckle std. dev. <2e-10 at 3 $\lambda/D$

These parameters drift linearly during the observation which may last several hours.

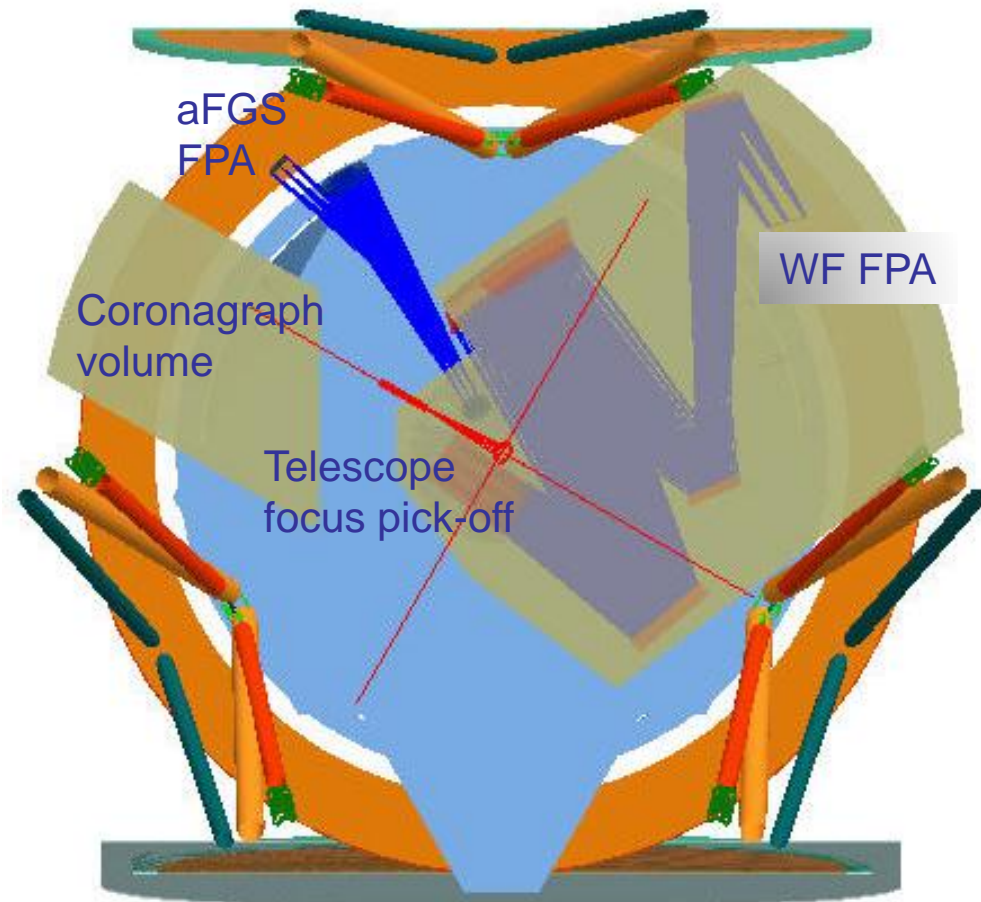Std. dev. of the amplitude of the linear drift.

Change in image plane uniformity if the given parameter changes by 2x its allocation.

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| Parameter | Allocation (1 sigma) | $d\sigma$ |
|---|---|---|
| Secondary mirror axial motion | 5 nm | 5.30E-11 |
| Telescope rigid body pointing | 15 mas | 4.90E-11 |
| Secondary mirror x or y tilt | 10 nrad | 1.30E-11 |
| Secondary mirror lateral motion | 5 nm | 9.00E-12 |
| Primary mirror coma | 10 pm | 7.00E-12 |
| Primary mirror sph. astig. | 10 pm | 6.00E-12 |
| Primary mirror focus | 30 pm | 3.30E-12 |
| Primary mirror spherical aber. | 10 pm | 2.20E-12 |

*These allocations may change substantially over the course of the study. Allocations assume low-order wavefront sensor sees only tip-tilt.*

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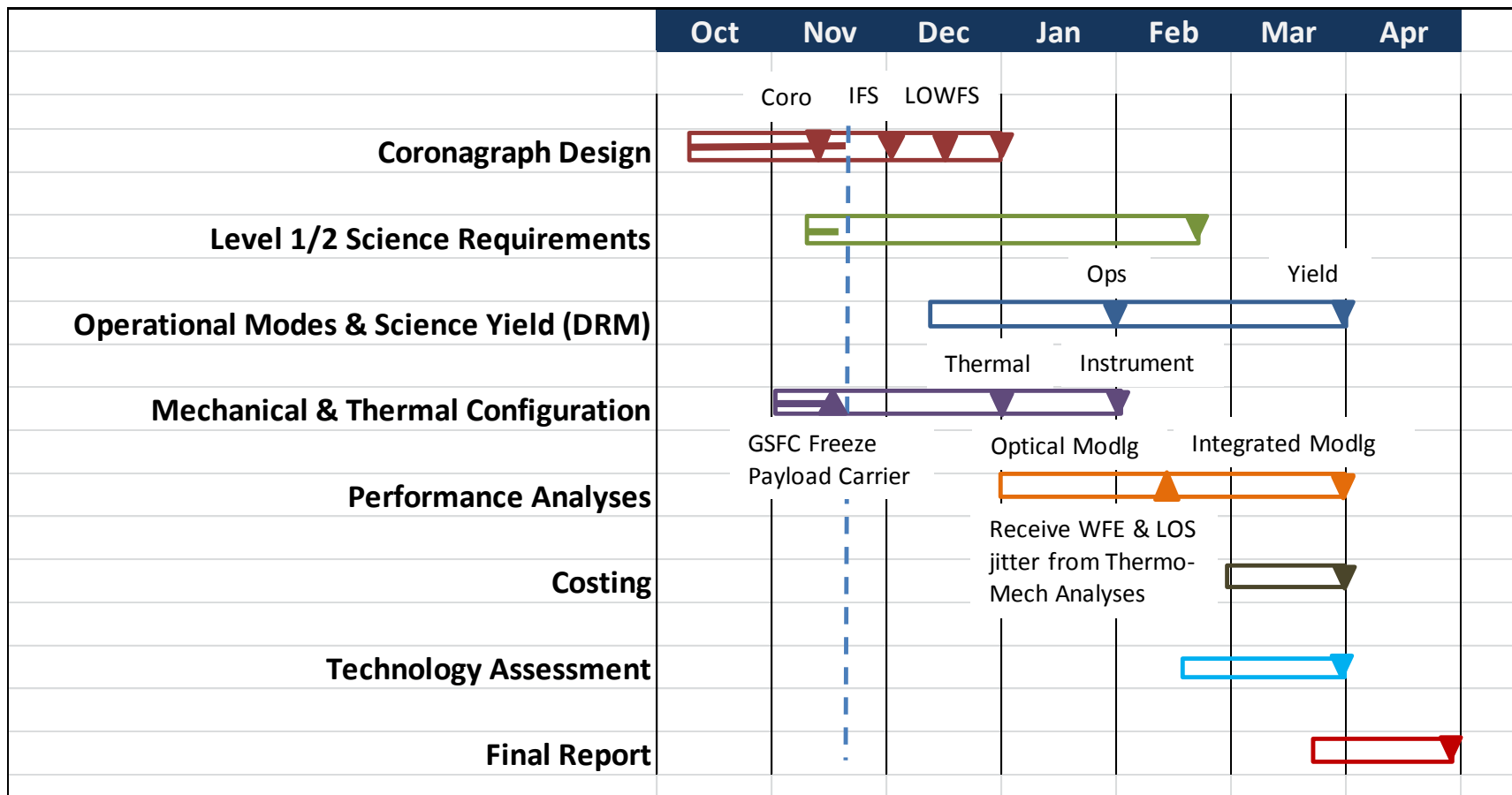
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- Goals:
  - axially and radially separate all 3 channels
  - Allow modularity and accessibility for servicing
  - Co-locate room-temp Coronagraph & aFGS
  - Radially place FPAs outward

- Note – what is shown is not original strut configuration,



aFGS FPA

WF FPA

Coronagraph volume

Telescope focus pick-off

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|  | Oct | Nov | Dec | Jan | Feb | Mar | Apr |
|---|---|---|---|---|---|---|---|

**Coronagraph Design** — Coro, IFS, LOWFS

**Level 1/2 Science Requirements**

**Operational Modes & Science Yield (DRM)** — Ops, Yield

**Mechanical & Thermal Configuration** — Thermal, Instrument

**Performance Analyses** — GSFC Freeze Payload Carrier, Optical Modlg, Integrated Modlg

**Costing** — Receive WFE & LOS jitter from Thermo-Mech Analyses

**Technology Assessment**

**Final Report**

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- Main Concerns:
  - Broadband Coronagraph performance w/ obscured telescope
  - Observing Stability: Driven by temperature transients & jitter

- Anticipated technical challenges
  - Coronagraph chromaticity & throughput
  - Impact of increased obscuration for straylight control
  - Observatory operations at cold temperatures
    - telescope materials optimized for room temperature
    - coronagraph operations at RT
  - Orbit: GEO vs L2

- Analyses will provide inputs for future design cycles:
  - Optimize coronagraph for science, stability and straylight
  - Possible improved thermal and vibration multi-stage control

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- **Ideal Optical Performance of AFTA Coronagraph:**
  - Fresnel propagation through all optics including surface errors (figuring, thermal) & WFSC
    - **MACOS** for alignment sensitivities budget verification,
    - **Proper** (J. Krist) for simulation of wavelength dependt speckles & holes around target source
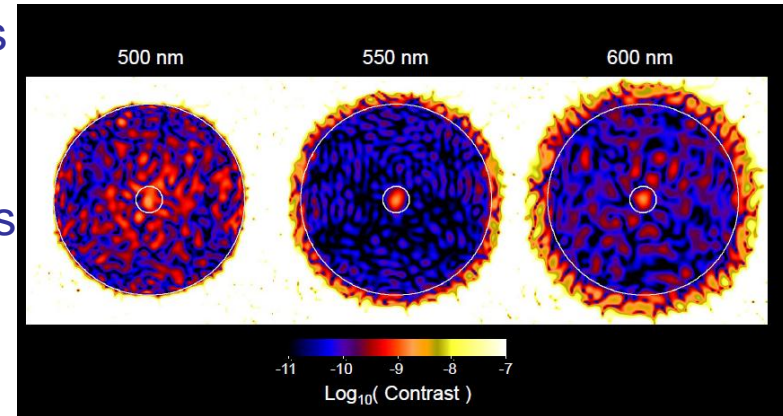


*J. Krist, Exopag June 2011*
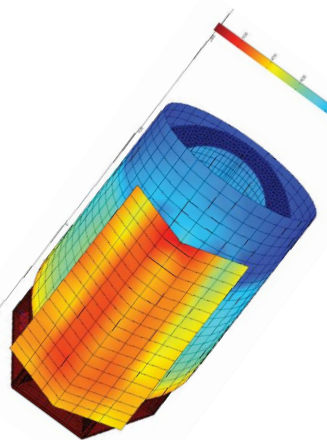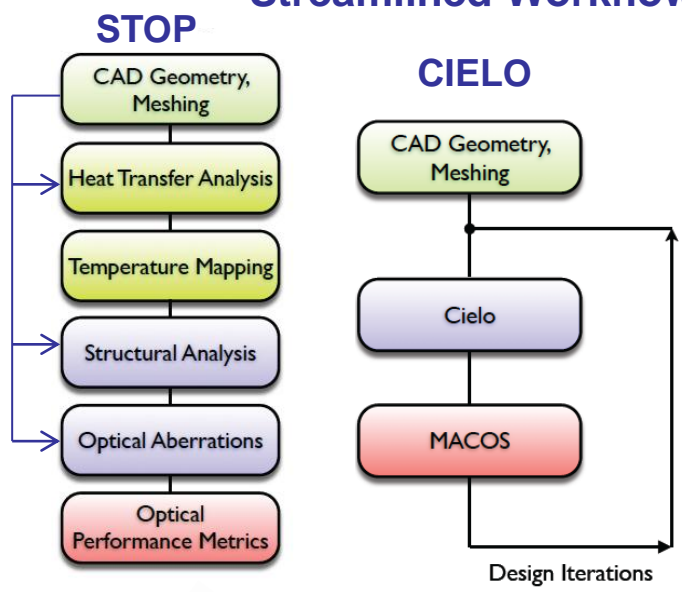
- **Thermal-Structural Integrated Analyses**:
  - Inputs to MACOS/PROPER from GSFC & JPL traditional STOP analyses
    - Issues w/ meshing, accuracy, active control
  - Demonstration of new ExEP Technology: **CIELO**
    - Single high fidelity model for thermal-structures-optics
    - Temperature dependent material properties, orbit analyses, …
    - Enables direct computation of contrast to transient deformations w/ or w/o active control in the loop: DM WFSC, LOWFS, thermal control.
    - Decomposed into zernickes for direct comparison to error budgets
    - Demonstrated on PECO

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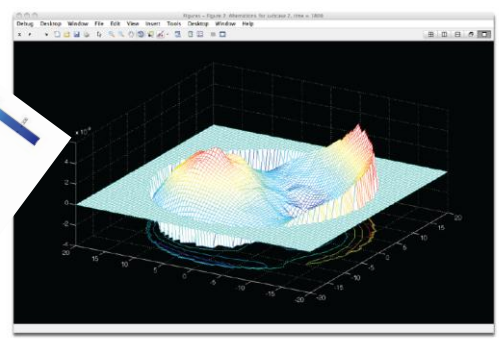**Jet Propulsion Laboratory**
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**Streamlined Workflow**

**STOP**

CAD Geometry, Meshing

Heat Transfer Analysis

Temperature Mapping

Structural Analysis

Optical Aberrations

Optical Performance Metrics

**CIELO**

CAD Geometry, Meshing

Cielo

MACOS

Design Iterations

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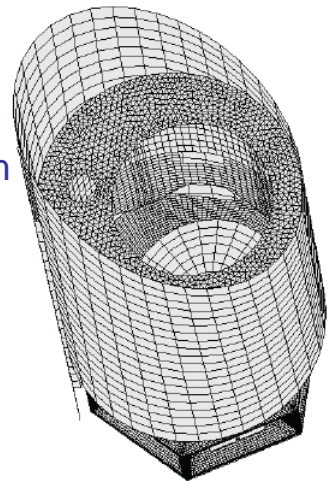
**Telescope Temperatures**

**Primary Mirror Response**

**PECO Model:**

- 40K Radiation Exchange surfaces
- 500K Structural degs of freedom

**Example Simulation** :

- 10 degree roll about boresight
- 6 hour Transient response
- Wavefront sensing in the loop

Contrast from RB Modes (FSM and Wavefront Control):



Contras from Aberrations with FSM and DM Control (Primary Mirror Rigid Body Modes)

- focus
- 45 Astigmatism
- 0 Astigmatism
- X-coma
- y-coma
- trefoil
- trefoil
- aspherical
- Spher Astigmatism
- Spher Astigmatism
- Quartrefoil
- Quartrefoil
- Total Contrast